ADCIRC v55

MODELING THE EARTH, MESH RESOLUTION EFFECTS, AND REMOVING TIME STEP CONSTRAINTS

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OVERVIEW OF COASTAL OCEAN MODELS

O.B. Fringer, C.N. Dawson, R. He et al. — Ocean Modelling 143 (2019) 101458

Table 1
Models mentioned in this paper, in alphabetical order by model name. In the grid/variable placement column, B and C refer to the grid types of Arakawa and Lamb (1977).

Model	Citation	C: Coastal, R: Regional, G: Global	Finite-volume (FV) or Finite-element (FE)	Grid/variable placement	Vertical coordinate	Developer (s) present?	Notes/unique features
ADCIRC	Luettich et al. (1992) Westerink et al. (1994)	C	FE		Sigma	Blaine, Luettich, Westerink	Continuous/Discontinuous Galerkin
COAWST	Warner et al. (2008, 2010)	C/R	FV	C	Sigma	Signell, He, Ganju	Coupled Atmo-sphere/wave/sediment
COSINE	Chai et al. (2002, 2003, 2007)	C/R	–	–	–	Chai	Biogeochemical model
Delft3D-Flow/Delft3D-FM	oss.deltares.nl/web/deflt3d/home	C	FV	C	Sigma	No	
ECOM-si/POM	Blumberg and Mellor (1987)	C/R	FV	C	Sigma	No	
FunwaveC	Feddersen et al. (2011)	C	FV	C	2D (x-y)	Kirby, Shi	2D Boussinesq wave model
FVCOM	Chen et al. (2003)	C/R/G	FV	B	Sigma	Chen	
GETM	Burchard and Bolding (2002)	C	FV	C	Sigma/Adaptive	Burchard	Numerical mixing analysis
GOTM	Burchard et al. (1999)	C	–	–	1D (Z)	Burchard	Turbulence Model
HYCOM	Bleck and Boudra (1981)	R/G	FV	C	Sigma/Z/Isopycnal	No	Hybrid/Isopycnal coordinates
MARS3D	Lazure and Dumas (2008)	C/R	FV	C	Sigma	No	
MITgcm	Marshall et al. (1997a)	C/R/G	FV	C	Z	No	Shaved cells
NHWAVE	Ma et al. (2012) Shi et al. (2015)	C	FV	C	Sigma	Kirby, Shi	Nonhydrostatic 3D wave model, LES
ROMS	Shchepetkin and McWilliams (2005)	R	FV	C	Sigma	Wilkin	
SCHISM	Zhang et al. (2016)	C/R	FV/FE	C/FE	Z/Sigma	Zhang	Locally-adaptive vertical coordinate
SELFE	Zhang and Baptista (2008)	C	FV/FE	C	Z/Sigma	Zhang, Baptista	
SLIM	Vallaeys et al. (2018)	C/R	FE		Z/Sigma/ Adaptive	No	Discontinuous Galerkin
SUNTANS	Fringer et al. (2006)	C	FV	C	Z	Fringer	
SWAN	Booij et al. (1999)	C/R	FV	C	2D (x-y)	No	Phase-averaged wave model
SWASH	Zijlema et al. (2011)	C	FV	C	Sigma	No	2D/3D Boussinesq wave model
TRIM/UnTRIM	Casulli (1999), Casulli and Zanolli (2002, 2005)	C	FV	C	Z	No	Subgrid bathymetry
WaveWatch III	Tolman (2009)	R/G	FV	C	2D (x-y)	No	Phase-averaged wave model
WRF-Hydro	Gochis et al. (2018)	C/R	–	–	–	No	Atmospheric/hydrological model

- **ADCIRC** is considered only a **coastal** model
- Continuous Galerkin Finite-Element method (**CG-FEM**)
- Uses **GWCE** formulation to avoid high-frequency oscillations in **CG-FEM** method

AIMS

1) Extend **ADCIRC** to a **global** model
   a. Show improvement over old version
   b. Mesh resolution sensitivities

2) Improve **stability and mass-conservation** issues associated with **GWCE** formulation

- Note: **CG-FEM** method is nice because we can keep **2nd order** accuracy and have a lot of **tolerance for skewed elements** (Fringer et al., 2019)

O.B. Fringer, C.N. Dawson, R. He et al.

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ADCIRC	Luettich et al. (1992) Westerink et al. (1994)	C/R/G	FE
COAWST	Warner et al. (2008, 2010)	C/R	FV
COSINE	Chai et al. (2002, 2003, 2007)	C/R	–
Delft3D-Flow/Delft3D-FM	oss.deltares.nl/web/delft3d/home	C	FV
ECOM-si/POM	Blumberg and Mellor (1987)	C/R	FV
FunwaveC	Feddersen et al. (2011)	C	FV
FVCOM	Chen et al. (2003)	C/R/G	FV
GETM	Burchard and Bolding (2002)	C	FV
GOTM	Burchard et al. (1999)	C	–
HYCOM	Bleck and Boudra (1981)	R/G	FV
MARS3D	Lazure and Dumas (2008)	C/R	FV
MITgcm	Marshall et al. (1997a)	C/R/G	FV
NHWAVE	Ma et al. (2012) Shi et al. (2015)	C	FV
ROMS	Shchepetkin and McWilliams (2005)	R	FV
SCHISM	Zhang et al. (2016)	C/R	FV/FE
SELFE	Zhang and Baptista (2008)	C	FV/FE
SLIM	Vallaeys et al. (2018)	C/R	FE
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WaveWatch III	Tolman (2009)	R/G	FV
WRF-Hydro	Gochis et al. (2018)	C/R	–

1) EXTENDING ADCIRC TO GLOBAL MODEL

Currently, *tan(ϕ)* terms ignored…

$$\frac{1}{R\cos\phi}\frac{\partial(VH\cos\phi)}{\partial\phi} = \frac{1}{R}\frac{\partial(VH)}{\partial\phi} - \cancelto{0}{\frac{\tan\phi}{R}VH}$$

$$\frac{\partial\zeta}{\partial t} = -\frac{1}{R\cos\phi}\left[\frac{\partial(UH)}{\partial\lambda} + \frac{\partial(VH\cos\phi)}{\partial\phi}\right] \tag{1}$$

$$\begin{aligned}\frac{\partial U}{\partial t} = &-\frac{U}{R\cos\phi}\frac{\partial U}{\partial\lambda} - \frac{V}{R}\frac{\partial U}{\partial\phi} - (\mathcal{C}_{\lambda\phi} - f')V - \frac{1}{R\cos\phi}\frac{\partial\Psi}{\partial\lambda} + \tau_w U_w - (\tau_b + \mathcal{C}_{\lambda\lambda})U\\ &+ \frac{\nu_t}{R}\left[\frac{1}{\cos\phi}\frac{\partial\tau_{\lambda\lambda}}{\partial\lambda} + \frac{\partial\tau_{\lambda\phi}}{\partial\phi} - \cancelto{0}{\tan\phi(\tau_{\lambda\phi} + \tau_{\phi\lambda})}\right]\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial V}{\partial t} = &-\frac{U}{R\cos\phi}\frac{\partial V}{\partial\lambda} - \frac{V}{R}\frac{\partial V}{\partial\phi} - (\mathcal{C}_{\phi\lambda} + f')U - \frac{1}{R}\frac{\partial\Psi}{\partial\phi} + \tau_w V_w - (\tau_b + \mathcal{C}_{\phi\phi})V\\ &+ \frac{\nu_t}{R}\left[\frac{\partial\tau_{\phi\phi}}{\partial\phi} + \frac{1}{\cos\phi}\frac{\partial\tau_{\phi\lambda}}{\partial\lambda} + \cancelto{0}{\tan\phi(\tau_{\lambda\lambda} - \tau_{\phi\phi})}\right]\end{aligned} \tag{3}$$

$$f' = 2\Omega\sin\phi + \cancelto{0}{\frac{\tan\phi}{R}U}$$

CURRENT ADCIRC MODEL EQUATIONS

- **Main problem:**

$$\frac{1}{R\cos\phi}\frac{\partial(VH\cos\phi)}{\partial\phi}$$

Solving this term in continuity eq. directly is difficult with CG-FEM due to nonlinearity of the ϕ dependent terms..

$$= \frac{1}{R}\frac{\partial(VH)}{\partial\phi} - \cancelto{0}{\frac{\tan\phi}{R}}VH$$

- This expansion eliminates nonlinearity but the *tan(ϕ)* term is extremely stiff for the numerical method so it has just been ignored...

SOLUTION BY REFORMULATION

- Use an arbitrary cylindrical projection to map (λ,ϕ) onto (x,y): (Select desired p = 0, 1, 2)

ICS = 2 sans *tan(ϕ)* terms

(λ_0, ϕ_0) is arbitrary origin

$$x = R(\lambda - \lambda_0)\cos\phi_0$$

$$y = \begin{cases} R\sin\phi\sec\phi_0 & \text{if } p = 0 : \text{ Equal-area} \\ R\phi & \text{if } p = 1 : \text{ Equidistant (CPP)} \\ R\ln(\tan\phi + \sec\phi)\cos\phi_0 & \boxed{\text{if } p = 2 : \text{ Conformal (Mercator)}} \end{cases}$$

ICS = 20

ICS = 21

ICS = 22

- Multiply continuity by ***cos^p(ϕ)*** [= 1 when p = 0]:

$$\frac{\partial(\zeta\cos^p\phi)}{\partial t} = -L_x\frac{\partial(UH)}{\partial x} - L_y\frac{\partial(VH\cos\phi)}{\partial y}$$

$$L_x = \cos\phi_0(\cos\phi)^{p-1}, \qquad L_y = (\cos\phi_0)^{p-1},$$

Continuity in a nice form to solve!

this is just a constant

EQUATIONS ADCIRC NOW SOLVES

$$\frac{\partial^2(\zeta\cos^p\phi)}{\partial t^2} + \tau_0\frac{\partial(\zeta\cos^p\phi)}{\partial t} = -L_x\frac{\partial J_x}{\partial x} - L_y\frac{\partial(J_y\cos\phi)}{\partial y}$$

$$J_x = H\frac{\partial U}{\partial t} + U\frac{\partial\zeta}{\partial t} + \tau_0 UH$$

$$J_y = H\frac{\partial V}{\partial t} + V\frac{\partial\zeta}{\partial t} + \tau_0 VH$$

GWCE

τ_0 : just a constant here

$$\frac{\partial U}{\partial t} = -KU\frac{\partial U}{\partial x} - K^{p-1}V\frac{\partial U}{\partial y} - (\mathcal{C}_{xy} - f')V - K\frac{\partial\Psi}{\partial x} + \tau_w U_w - (\tau_b + \mathcal{C}_{xx})U + \nu_t\left[K\frac{\partial\tau_{xx}}{\partial x} + K^{p-1}\frac{\partial\tau_{xy}}{\partial y} - \tan\phi(\tau_{xy}+\tau_{yx})\right]$$

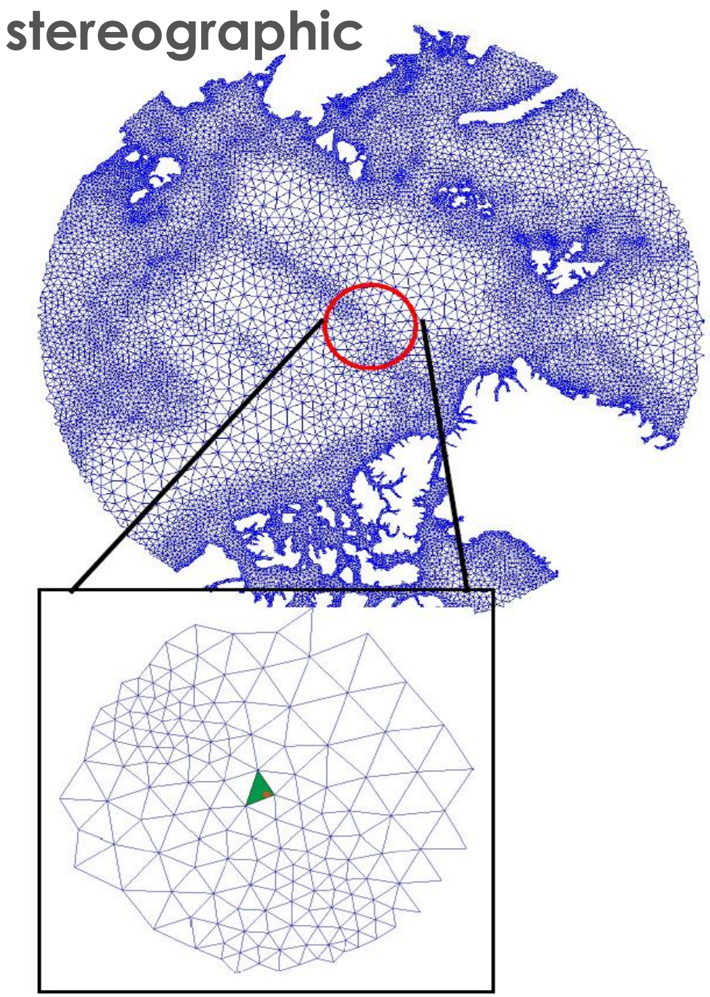
$$\frac{\partial V}{\partial t} = -KU\frac{\partial V}{\partial x} - K^{p-1}V\frac{\partial V}{\partial y} - (\mathcal{C}_{yx} + f')U - K^{p-1}\frac{\partial\Psi}{\partial y} + \tau_w V_w - (\tau_b + \mathcal{C}_{yy})V + \nu_t\left[K^{p-1}\frac{\partial\tau_{yy}}{\partial y} + K\frac{\partial\tau_{yx}}{\partial x} + \tan\phi(\tau_{xx}-\tau_{yy})\right]$$

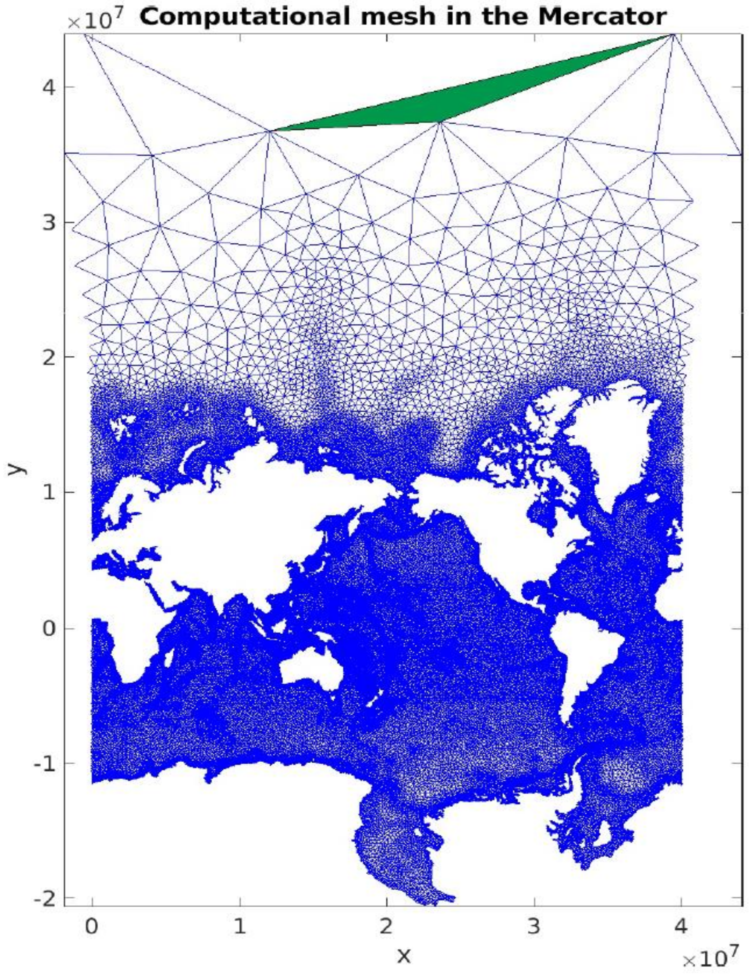
Momentum

POLE TREATMENT

☞ Strategy 1: do not nothing; requires that no FE node is placed at the pole.

MESH IN ARCTIC REGION

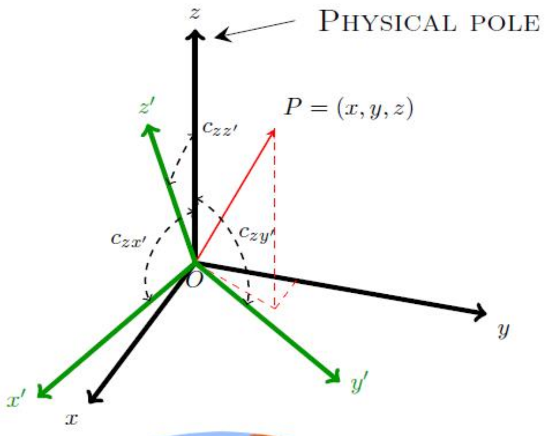


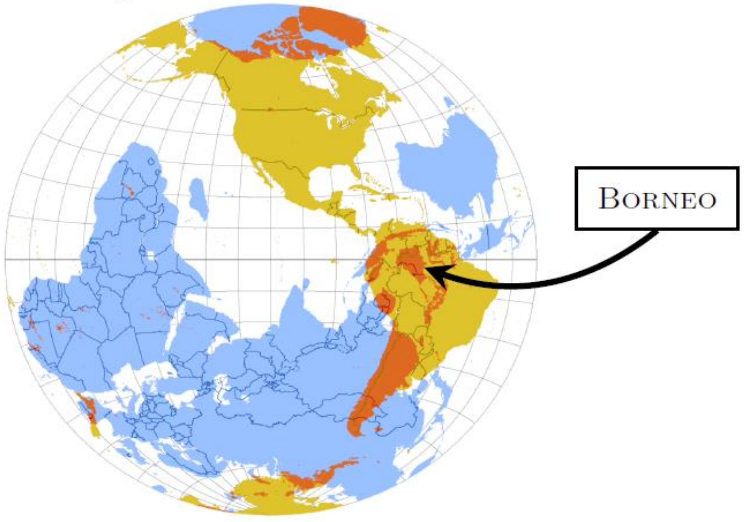


- Performs satisfactory but eventually suffers from numerical instability when the element straddling the pole having nodes very close to the pole.

POLE TREATMENT

☞ Strategy 2: rotate a computational pole so that it goes through lands.

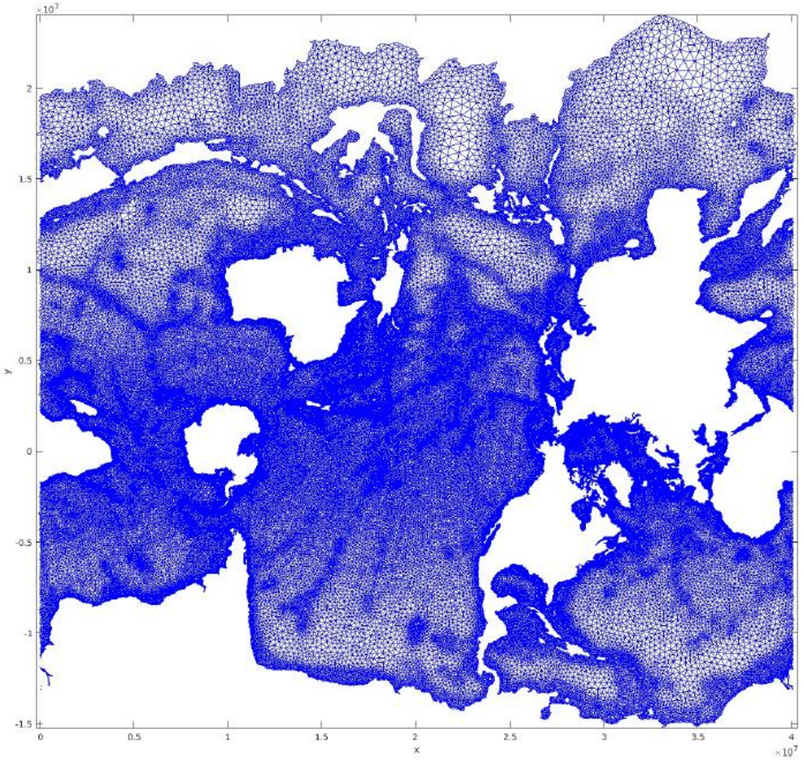




Antipoles map (from Wikipedia)

Computational Pole: Borneo-Brazil

Computational mesh in the Mercator projection



- Set **ICS** to a **negative** value, ex.: **ICS = -22**

  https://wiki.adcirc.org/wiki/ICS

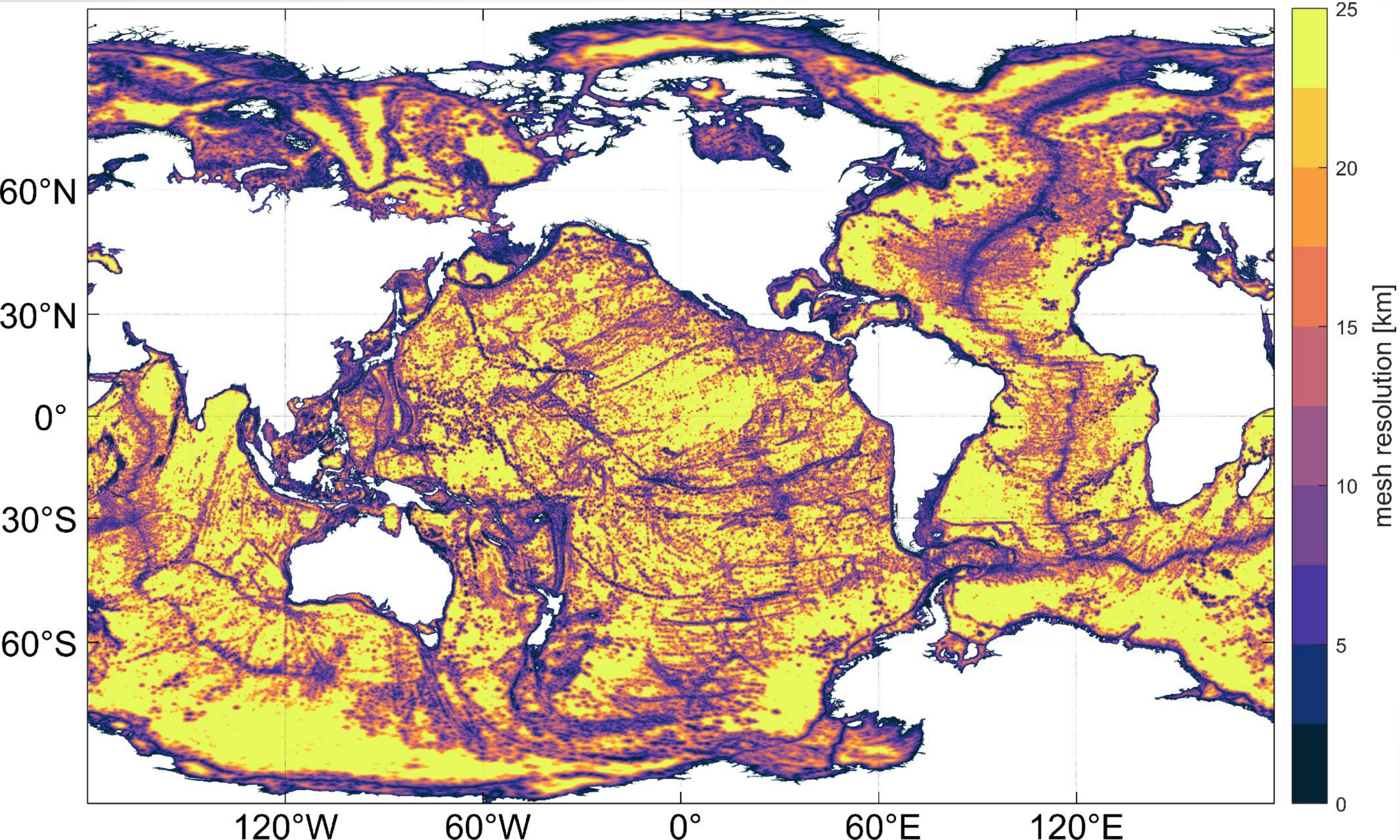
- Supply a **fort.rotm** file, ex.:
  znorth_in_spherical_coors
  114.16991 0.77432

  https://wiki.adcirc.org/wiki/Fort.rotm

- Allow the use of high mesh resolution at the physical pole.

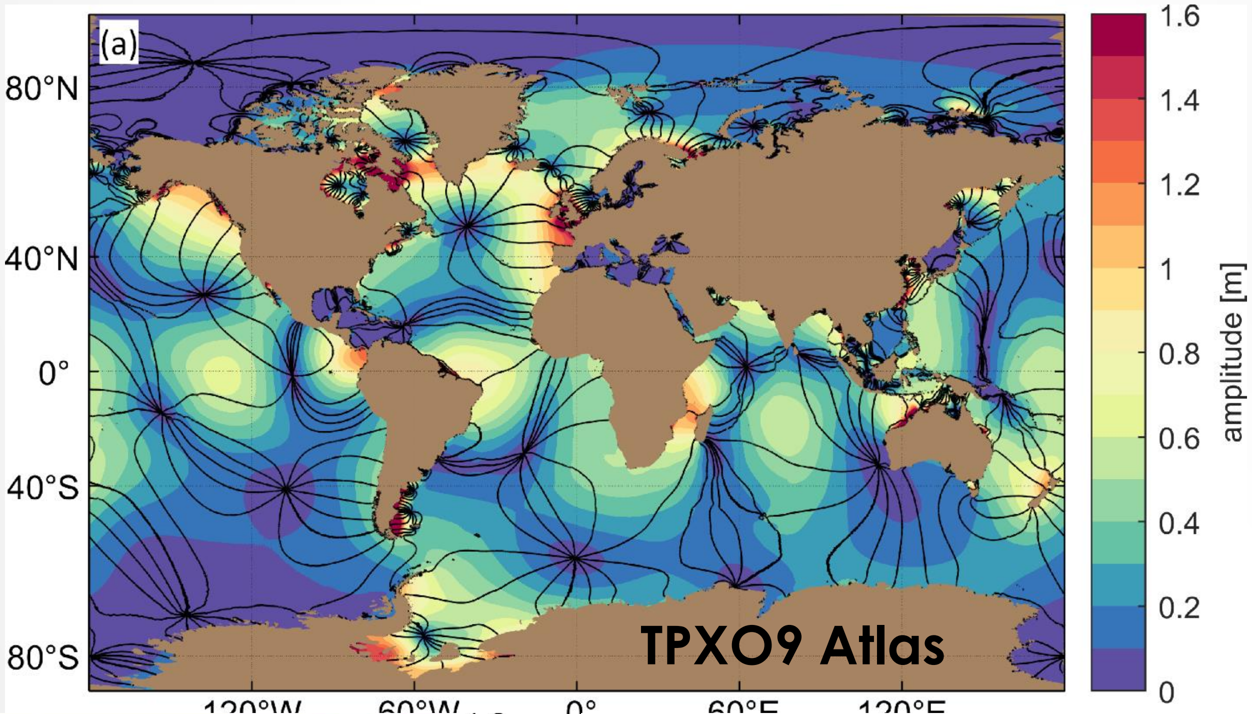
FIRST: TEST TIDES ON A HIGHLY RESOLVED MESH

Mesh rotated to have Greenland-Antarctica poles

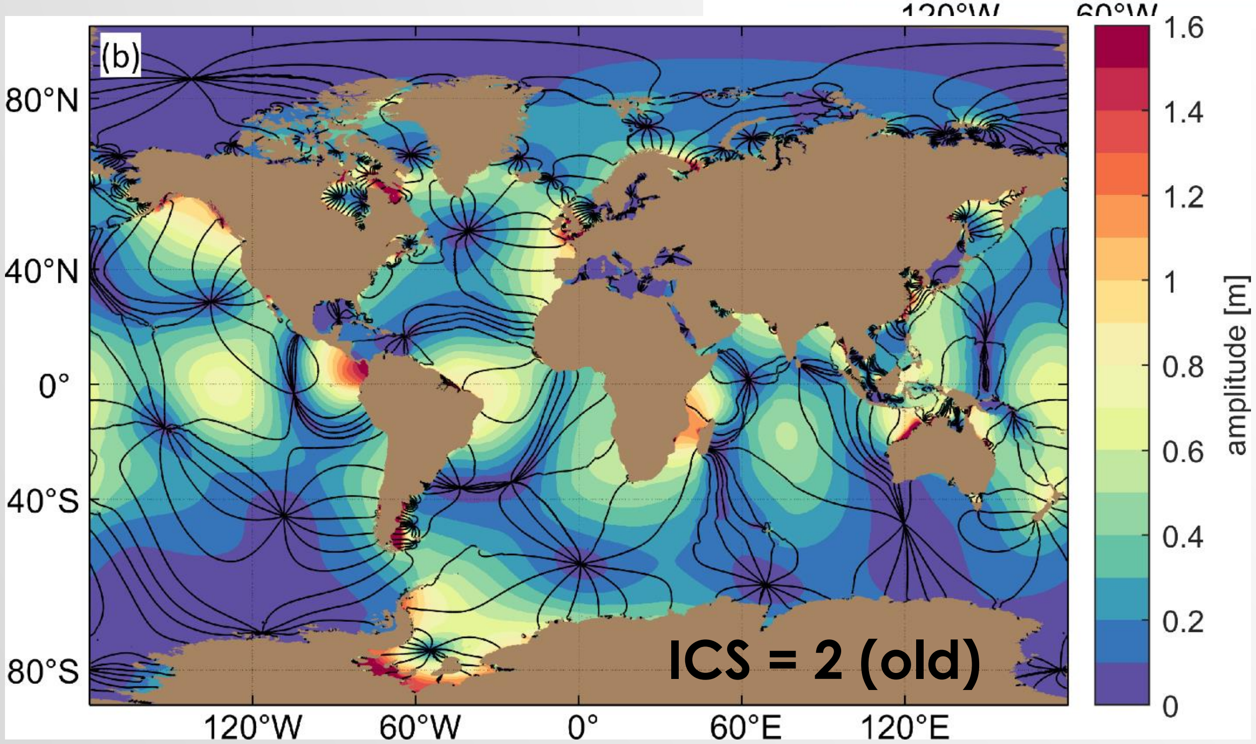


- Automatically generated by OceanMesh2D
  [See: Example_7_Global.m](Example_7_Global.m)
- 6 million vertices
- 1.5 km to 25 km resolution
- Highly resolved along topographic gradients

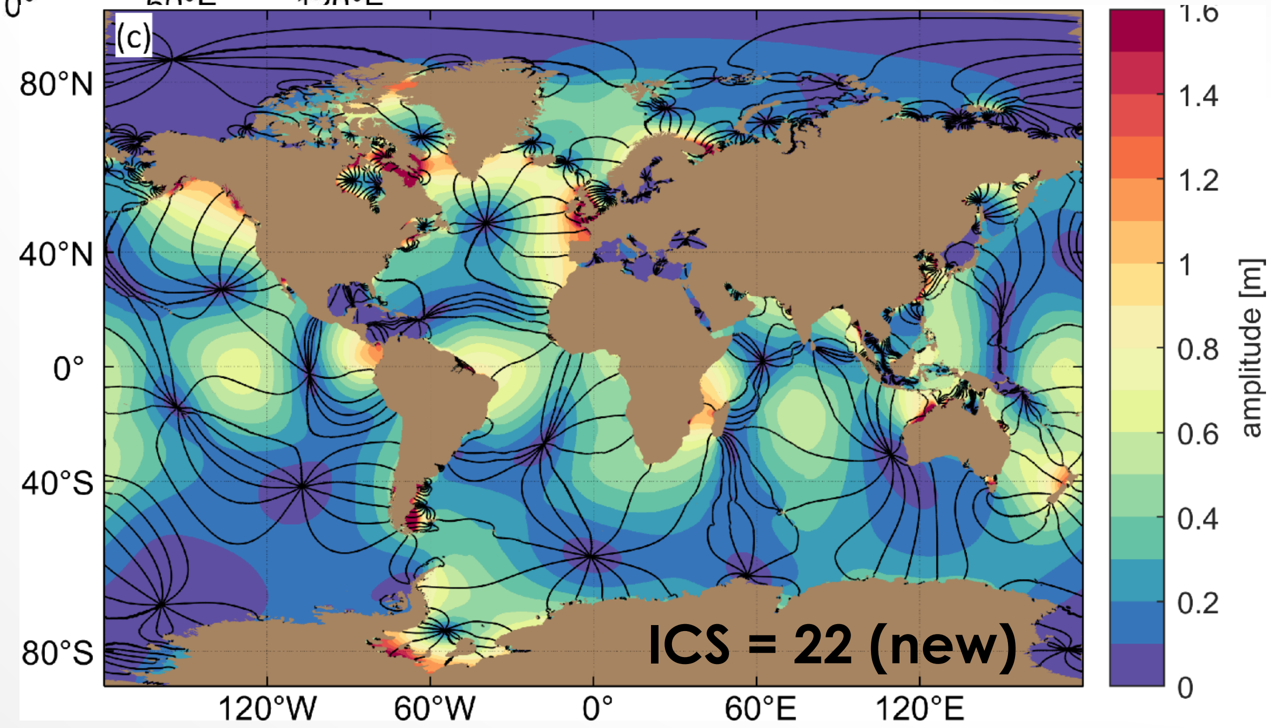
M2 TIDES



(a)
80°N
40°N
0°
40°S
80°S
120°W
60°W
0°
60°E
120°E
TPXO9 Atlas
amplitude [m]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0

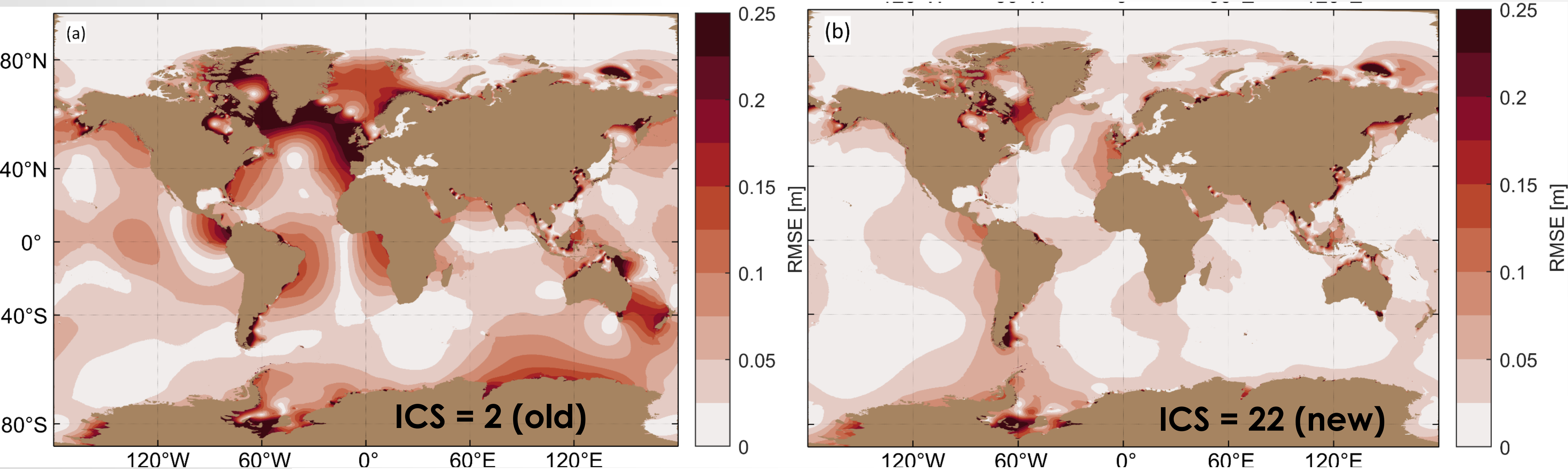


(b)
80°N
40°N
0°
40°S
80°S
120°W
60°W
0°
60°E
120°E
ICS = 2 (old)
amplitude [m]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0



(c)
80°N
40°N
0°
40°S
80°S
120°W
60°W
0°
60°E
120°E
ICS = 22 (new)
amplitude [m]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0

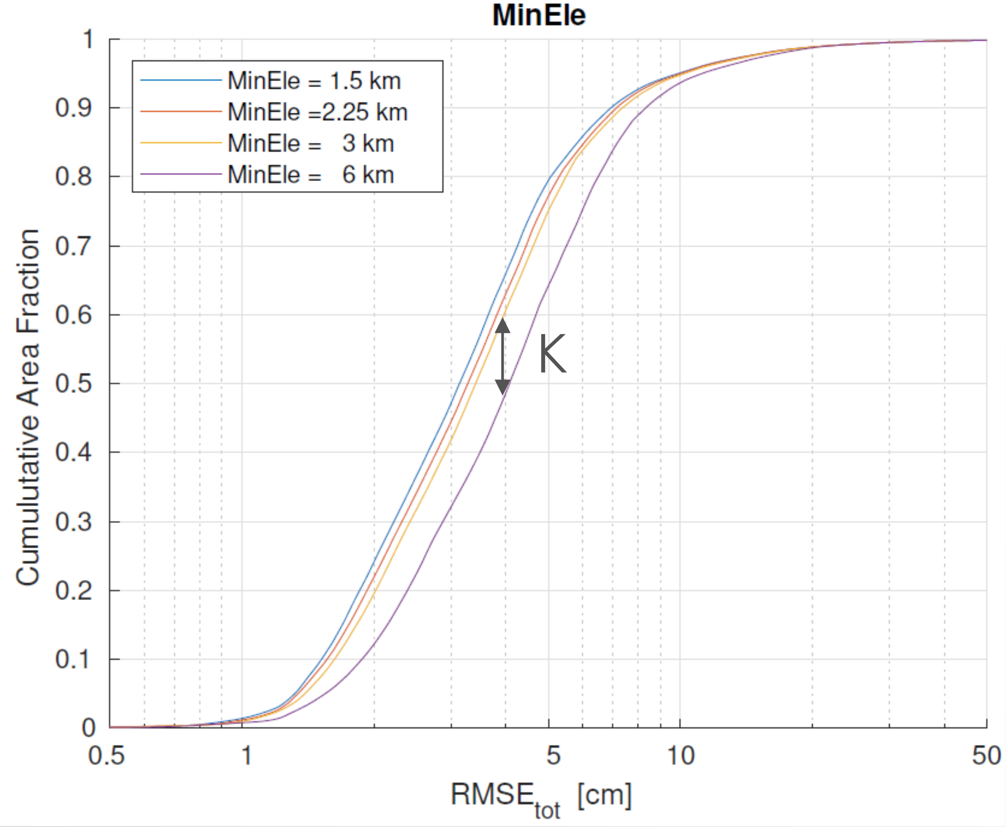
M2 RMSE

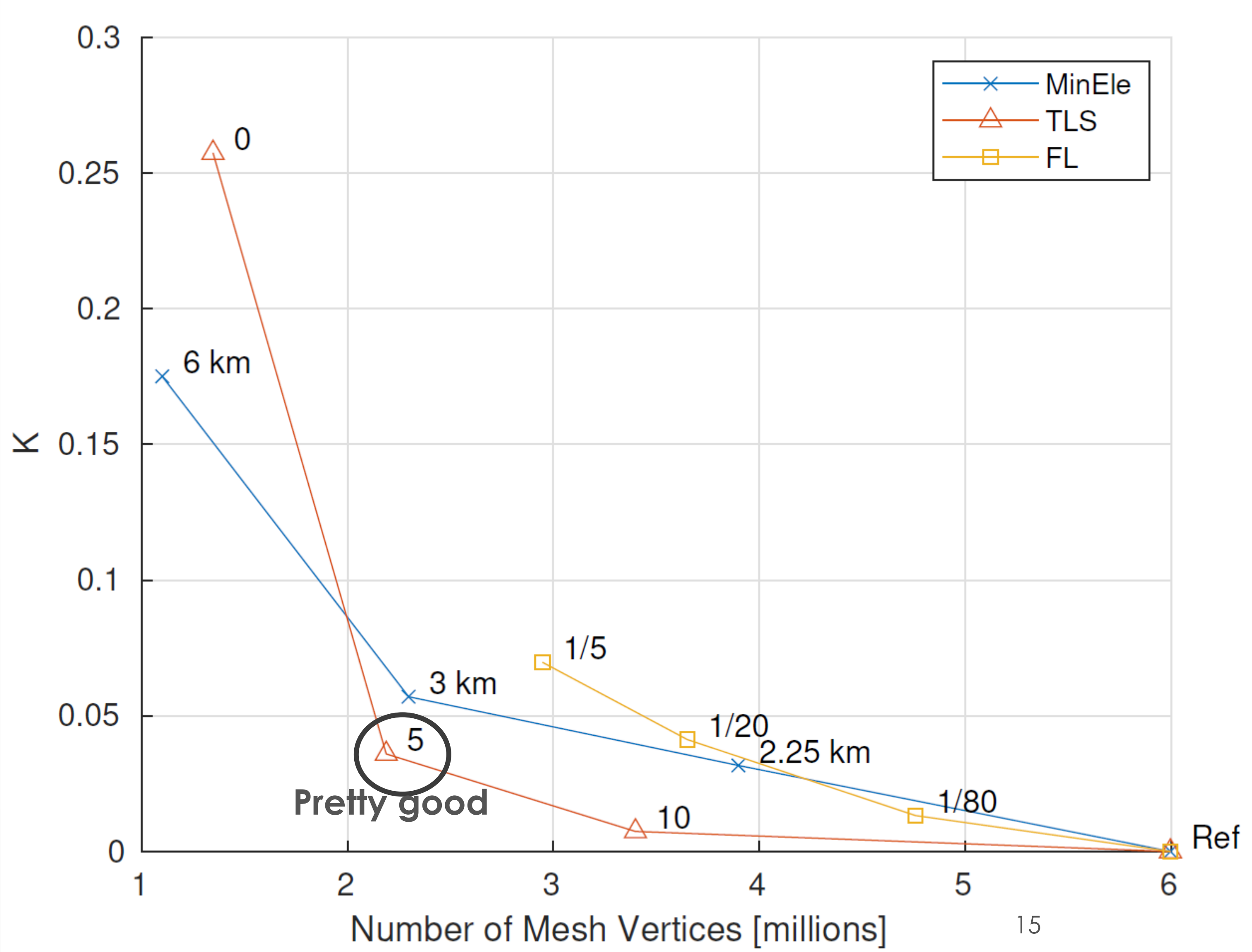


	M$_2$ $\overline{\text{RMSE}_t}$ [cm]		$\overline{\text{RMSE}_{t\|tot}}$ [cm] **[M2, N2, S2, K1, O1]**	
Model	Deep water	Shallow water	Deep water	Shallow water
ADCIRC v54 **ICS = 2 (old)**	6.5	18.5	7.92	22.1
ADCIRC v55 **ICS = 22 (new)**	2.87	13.9	3.89	17.2 **(Median = 6.67 cm)**
Stammer et al. (2014)*	5.25-7.76	18.6-27.9	-	-
Ngodock et al. (2016)*	2.6-3.2	-	-	-

*: $\overline{\text{RMSE}_t}$ is computed against TPXO8-Atlas rather than TPXO9-Atlas.

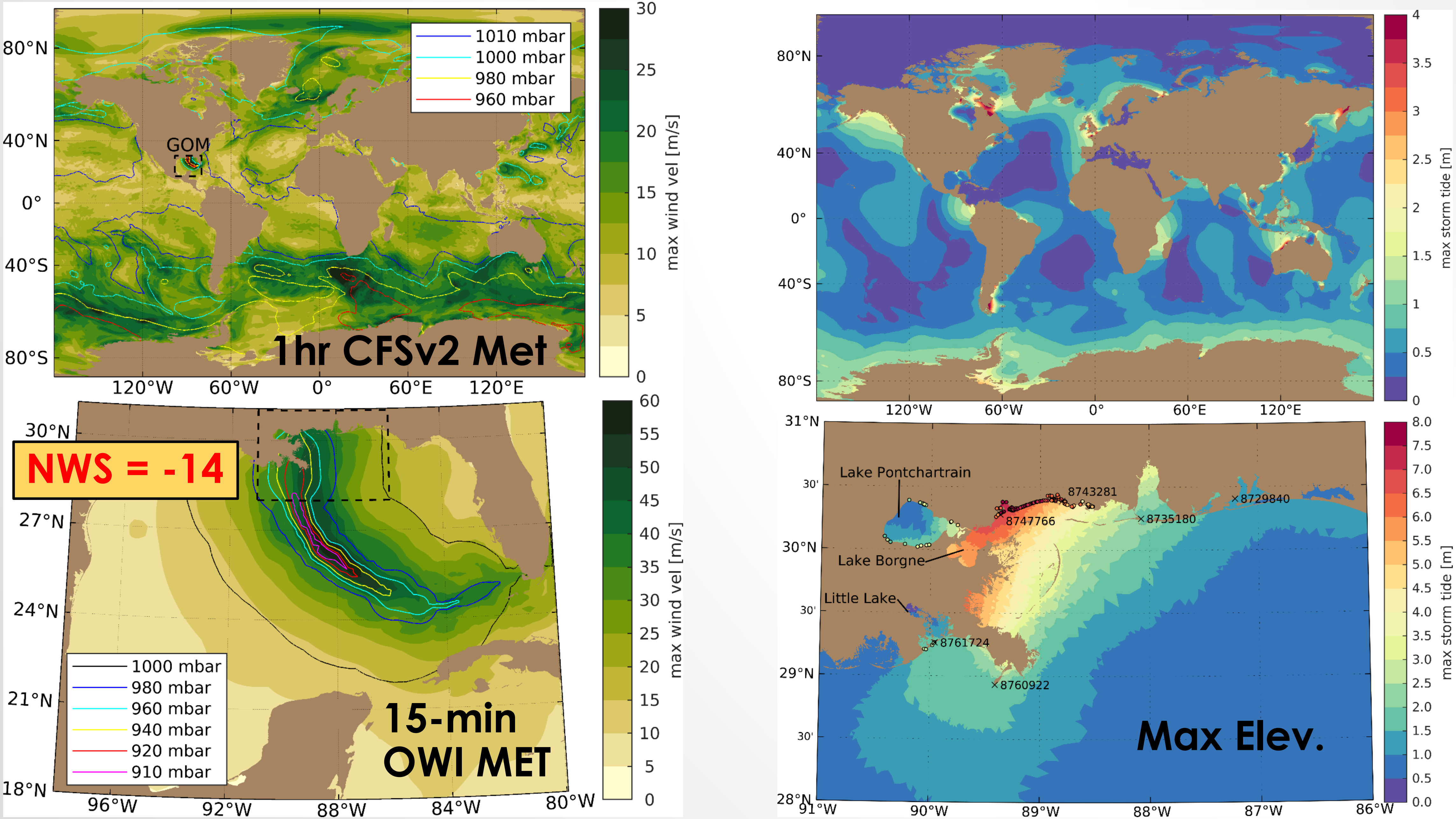
SENSITIVITY TO MESH RESOLUTION



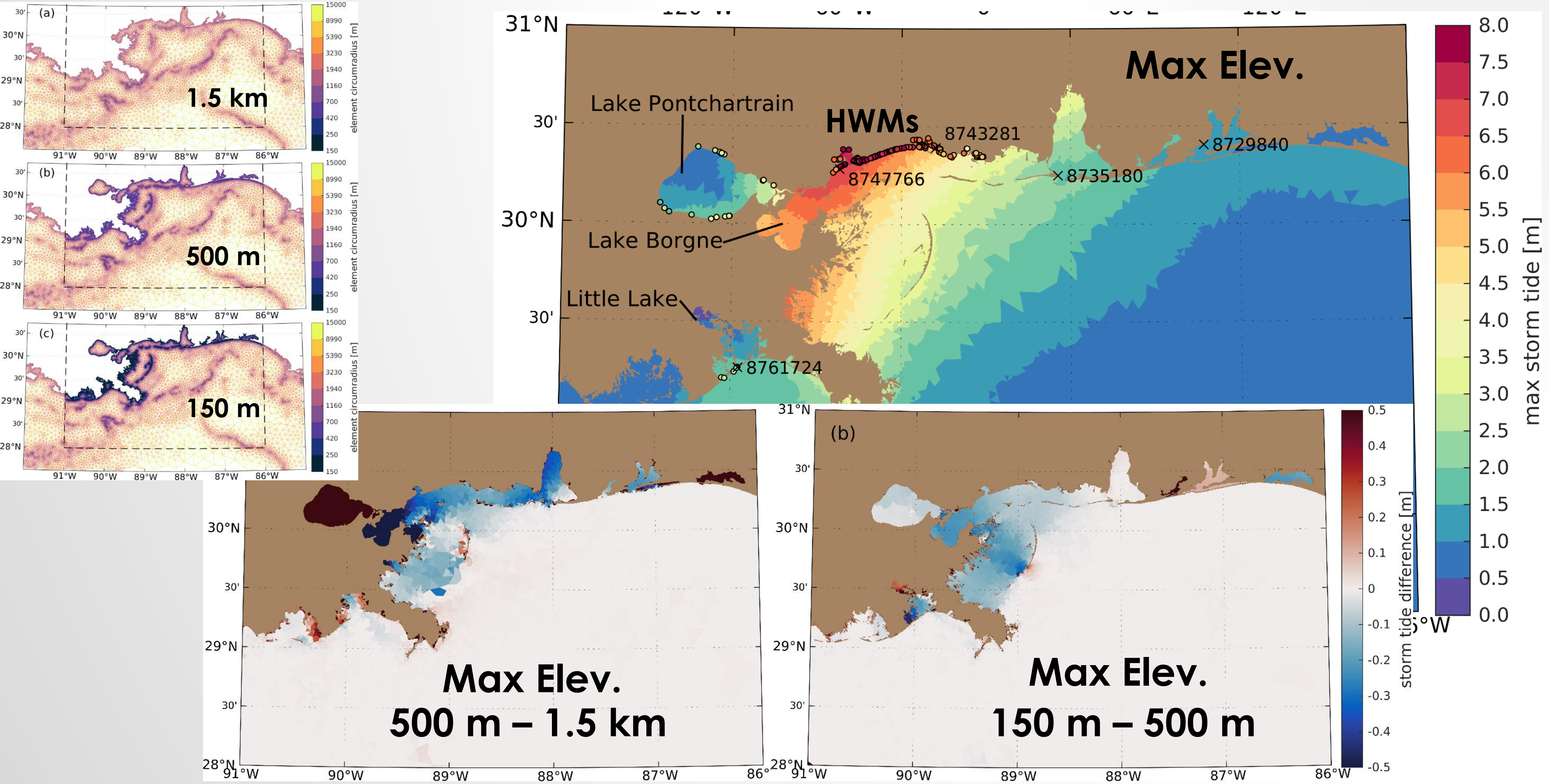


***edgefx* options in**
<u>OceanMesh2D</u>
MinEle = ‘h0’
TLS = ‘slp’
FL = ‘fl’

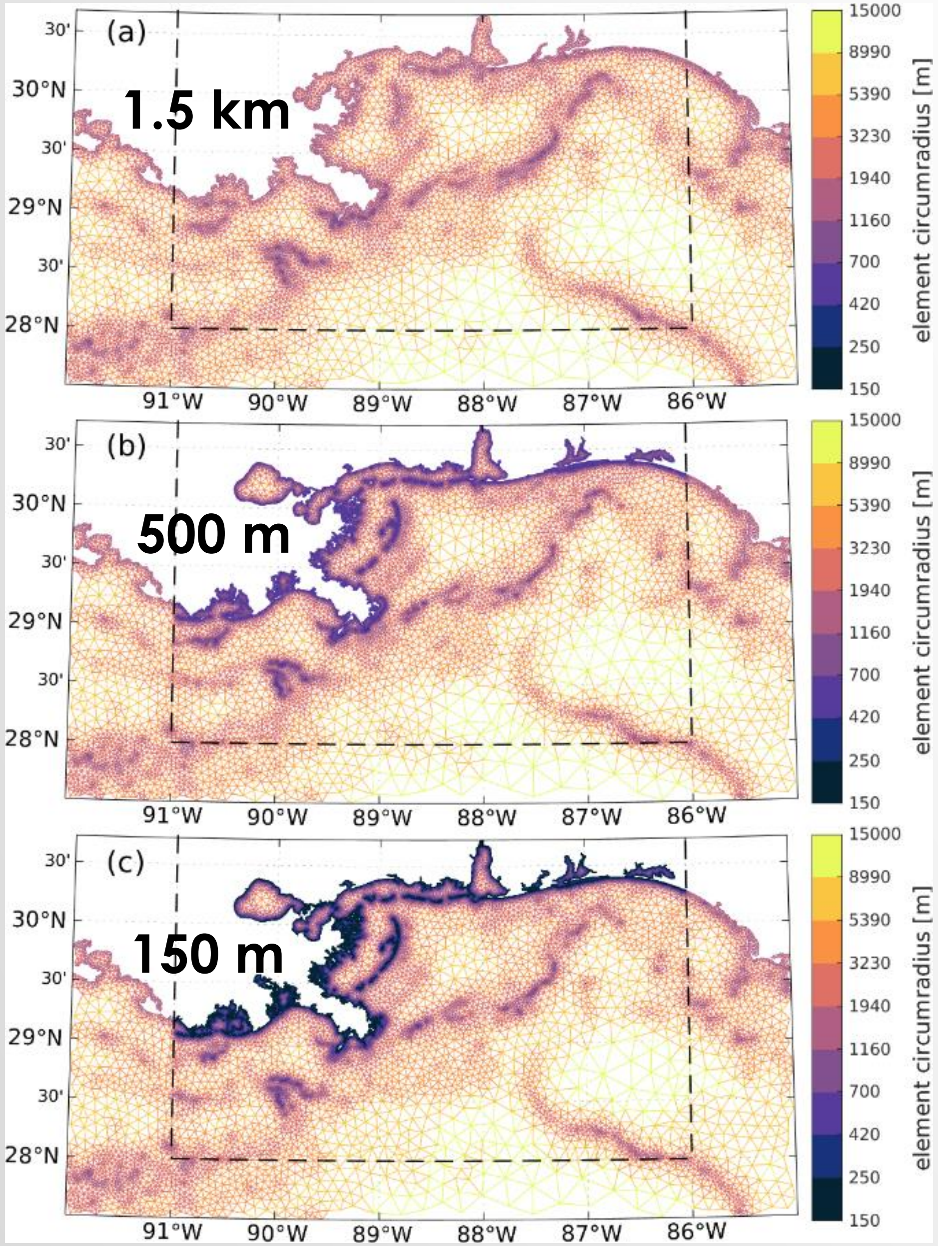
HURRICANE KATRINA ON GLOBAL MESH

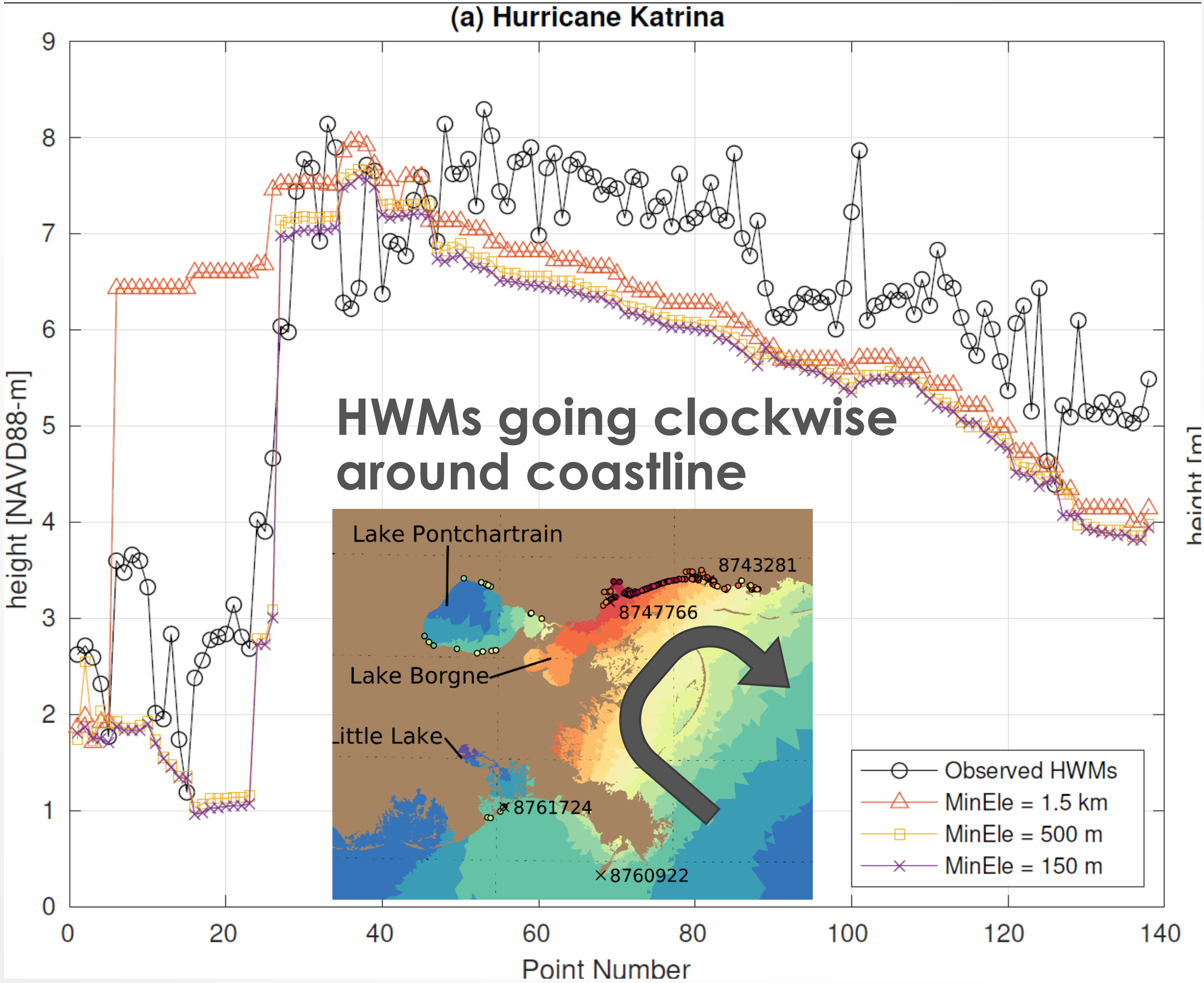


SENSITIVITY TO LOCAL MESH REFINEMENT



SENSITIVITY TO LOCAL MESH REFINEMENT





2) IMPROVING STABILITY AND MASS CONSERVATION ISSUES

- **What is the stability criteria for the GWCE? Let's check**

1D linear case:

$$\frac{\zeta^{*s+1}}{\Delta t}\left(\frac{1}{\Delta t}+\frac{\tau_0}{2}\right)+\alpha_1 gh\frac{\partial^2\zeta^{*s+1}}{\partial x^2}=\frac{\zeta^{*s}}{\Delta t}\left(\frac{1}{\Delta t}-\frac{\tau_0}{2}\right)$$
$$-(\alpha_1+\alpha_2)gh\frac{\partial^2\zeta^{s}}{\partial x^2}-\alpha_3 gh\frac{\partial^2\zeta^{s-1}}{\partial x^2}+(\tau_0-\tau_b^s)\frac{\partial U}{\partial x}^s$$

$$U^{s+1}\left(\frac{1}{\Delta t}+\frac{\tau_b^s}{2}\right)=U^s\left(\frac{1}{\Delta t}-\frac{\tau_b^s}{2}\right)-\frac{g}{2}\left(\frac{\partial\zeta^s}{\partial x}+\frac{\partial\zeta^{s+1}}{\partial x}\right)$$

Kinnmark, I. P. E.: The Shallow Water Wave Equations: Formulation, Analysis and Application, edited by C. A. Brebbia and S. A. Orszag, Springer Berlin Heidelberg, Berlin, Heidelberg., 1986.

I follow method outlined in Kinnmark (1986) monograph based on Routh-Hurwitz criterion.

1) Make assumption on relationship between $\alpha_1, \alpha_2, \alpha_3$ (A00, B00, C00):

$$\alpha_1 = \alpha_3 = \kappa, \text{ and } \alpha_2 = 1 - 2\kappa.$$

e.g., **0.35, 0.30, 0.35.** Kinnmark (1986) analyzed this one

Equation	$Cr \to \infty$	$\tau_0 \to \infty$
p_0	$\kappa \geq 1/4$	$\kappa < 1/4$ and $Cr^2 \leq \frac{1-m}{1-4\kappa}$
p_1	$\kappa \geq 1/4$ and $\tau_0 \leq 4\kappa\tau_b$	$Cr^2 \leq 4(m/2-1)^2$
p_2	none	none
p_3	none	none
Δ_2	$\boxed{\kappa \geq 1/4 \text{ and } \tau_0 \leq \tau_b}$	$Cr^2 \leq 4(m/2-1)^2$

i.e., **TAU0** must be less than **linear bottom friction everywhere!** (which is impossible for quadratic friction as **U → 0**)

$$\boxed{\tau_b = C_f \frac{U}{H}}$$

$$\frac{\zeta^{*s+1}}{\Delta t}\left(\frac{1}{\Delta t}+\frac{\tau_0}{2}\right)+\alpha_1 gh\frac{\partial^2\zeta^{*s+1}}{\partial x^2} = \frac{\zeta^{*s}}{\Delta t}\left(\frac{1}{\Delta t}-\frac{\tau_0}{2}\right)$$
$$-(\alpha_1+\alpha_2)gh\frac{\partial^2\zeta^s}{\partial x^2}-\alpha_3 gh\frac{\partial^2\zeta^{s-1}}{\partial x^2}+(\tau_0-\tau_b^s)\frac{\partial U^s}{\partial x}$$

$$U^{s+1}\left(\frac{1}{\Delta t}+\frac{\tau_b^s}{2}\right)=U^s\left(\frac{1}{\Delta t}-\frac{\tau_b^s}{2}\right)-\frac{g}{2}\left(\frac{\partial\zeta^s}{\partial x}+\frac{\partial\zeta^{s+1}}{\partial x}\right)$$

Alternative relationship between $\alpha_1, \alpha_2, \alpha_3$ (A00, B00, C00):

$$\alpha_1 = \alpha_2 = \kappa, \text{ and } \alpha_3 = 1 - 2\kappa$$

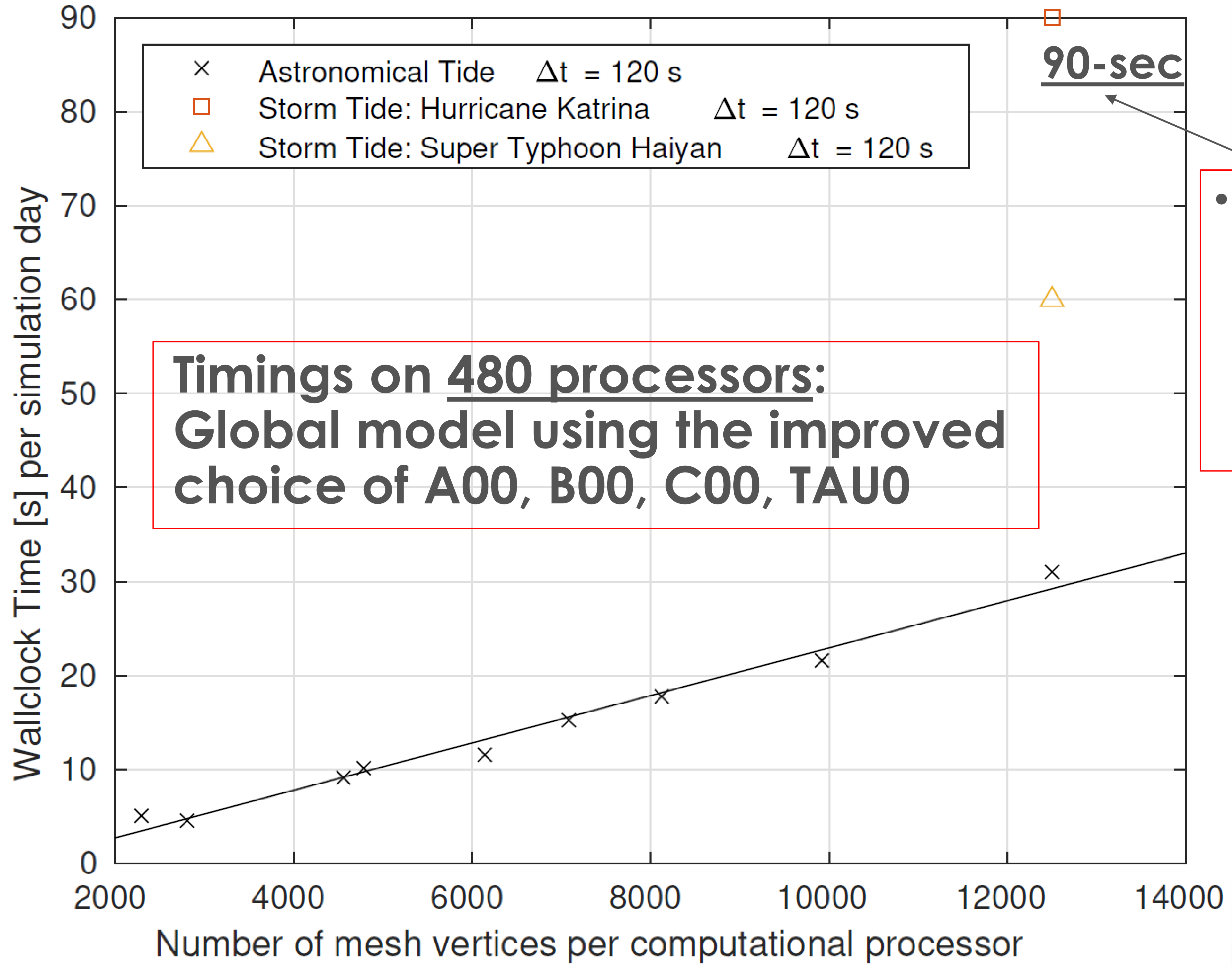
Equation	$Cr \to \infty$	$\tau_0 \to \infty$
p_0	$\kappa \leq 1/2$	$\kappa > 1/2$ and $Cr^2 \leq \frac{1-m}{2\kappa-1}$
p_1	$\boxed{1/3 \leq \kappa \leq 1/2 \text{ and } \tau_0 \Delta t \leq 4(2-m)(3\kappa-1)}$	$Cr^2 \leq 4(m/2-1)^2$
p_2	$\kappa \geq 1/3$	none
p_3	none	none
Δ_2	$\kappa \geq 1/3$	none

i.e., criteria between **TAU0** and **bottom friction vanishes!**

<u>Example:</u>
Select κ = 0.5, consistent mass-matrix: m = 2/3.
A00, B00, C00 = 0.5, 0.5, 0
TAU0 < 8/(3Δt)

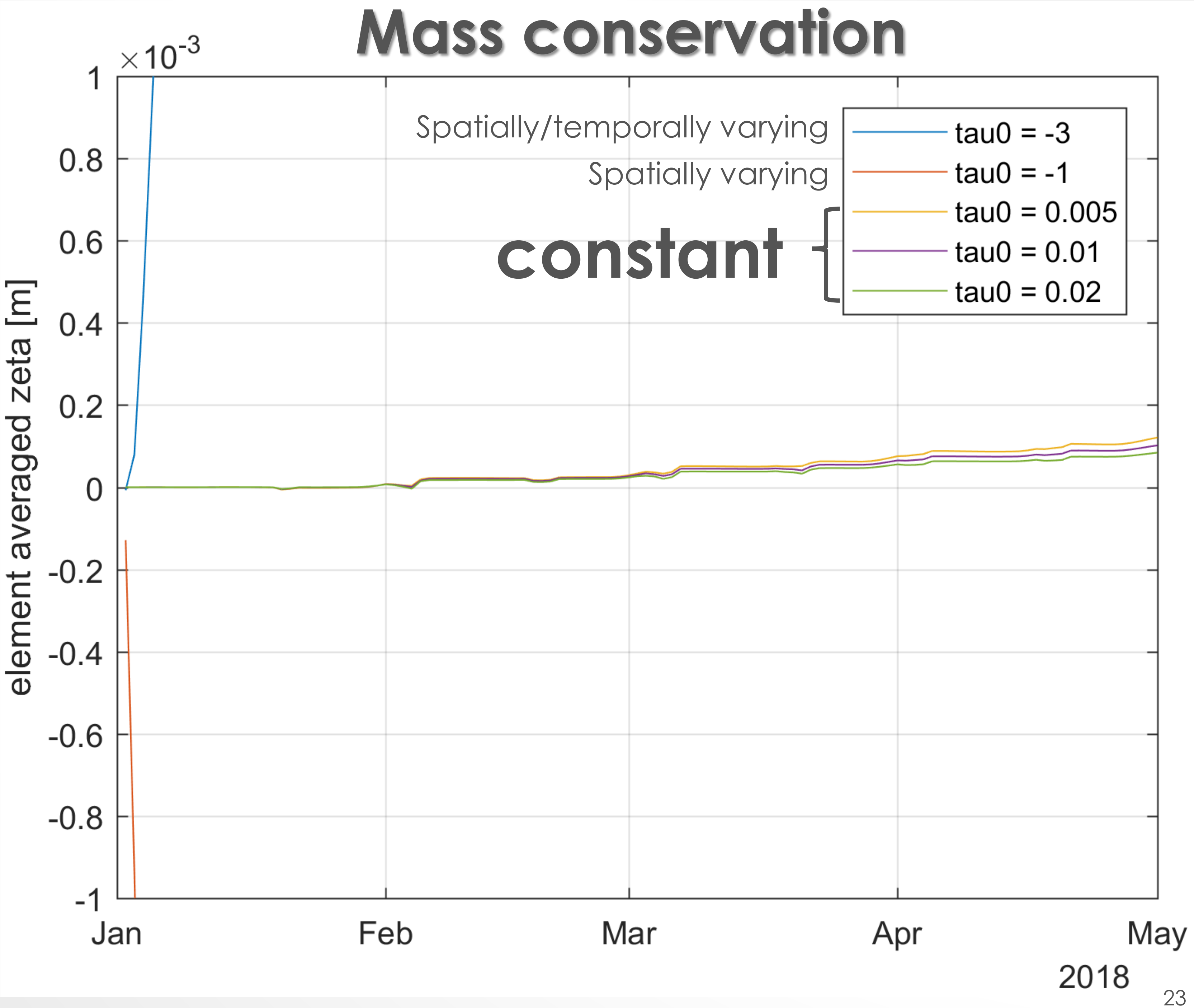
$$\frac{\zeta^{*s+1}}{\Delta t}\left(\frac{1}{\Delta t}+\frac{\tau_0}{2}\right)+\alpha_1 gh\frac{\partial^2\zeta^{*s+1}}{\partial x^2}=\frac{\zeta^{*s}}{\Delta t}\left(\frac{1}{\Delta t}-\frac{\tau_0}{2}\right)$$
$$-(\alpha_1+\alpha_2)gh\frac{\partial^2\zeta^{s}}{\partial x^2}-\alpha_3 gh\frac{\partial^2\zeta^{s-1}}{\partial x^2}+(\tau_0-\tau_b^s)\frac{\partial U^s}{\partial x}$$

$$U^{s+1}\left(\frac{1}{\Delta t}+\frac{\tau_b^s}{2}\right)=U^s\left(\frac{1}{\Delta t}-\frac{\tau_b^s}{2}\right)-\frac{g}{2}\left(\frac{\partial\zeta^s}{\partial x}+\frac{\partial\zeta^{s+1}}{\partial x}\right)$$



- Old Hurricane Katrina simulations (Dietrich et al., 2011): **DT = 1 sec**, ***60-min*** per simulation day on 480 processors

WHY WE SHOULD USE CONSTANT TAU0



SUMMARY

Pringle, W. J., et al. Global Storm Tide Modeling with ADCIRC v55 : Unstructured Mesh Design and Performance, will submit to Geosci. Model. Dev.

1) Extended **ADCIRC** to a **global** model
   a. Tide solutions with **ICS = -22** clearly improved from old version (ICS = 2)
   b. Resolution experiments show that global tide solutions decay beyond ~3 km min, and topographic slopes need to be well-resolved. Local refinement generally decreases open ocean max. storm tide elevations

2) Improved **stability and mass-conservation** issues associated with **GWCE** formulation
   a. Stability analysis shows that **A00, B00, C00 = 0.5, 0.5, 0** is non-Courant limited (in the linear sense) if **TAU0 < 8/(3Δt)**

      <u>Hurricane Katrina Examples:</u>
      Global **1.5 km** mesh runs with **Δt = 120 s**
      Locally refined **500 m** runs with **Δt = 120 s**
      Locally refined **150 m** mesh runs with **Δt = 50 s**

Also see: https://wiki.adcirc.org/wiki/IM for info on new option for fully implicit gravity wave term (**IM Digit 6 = 3**)

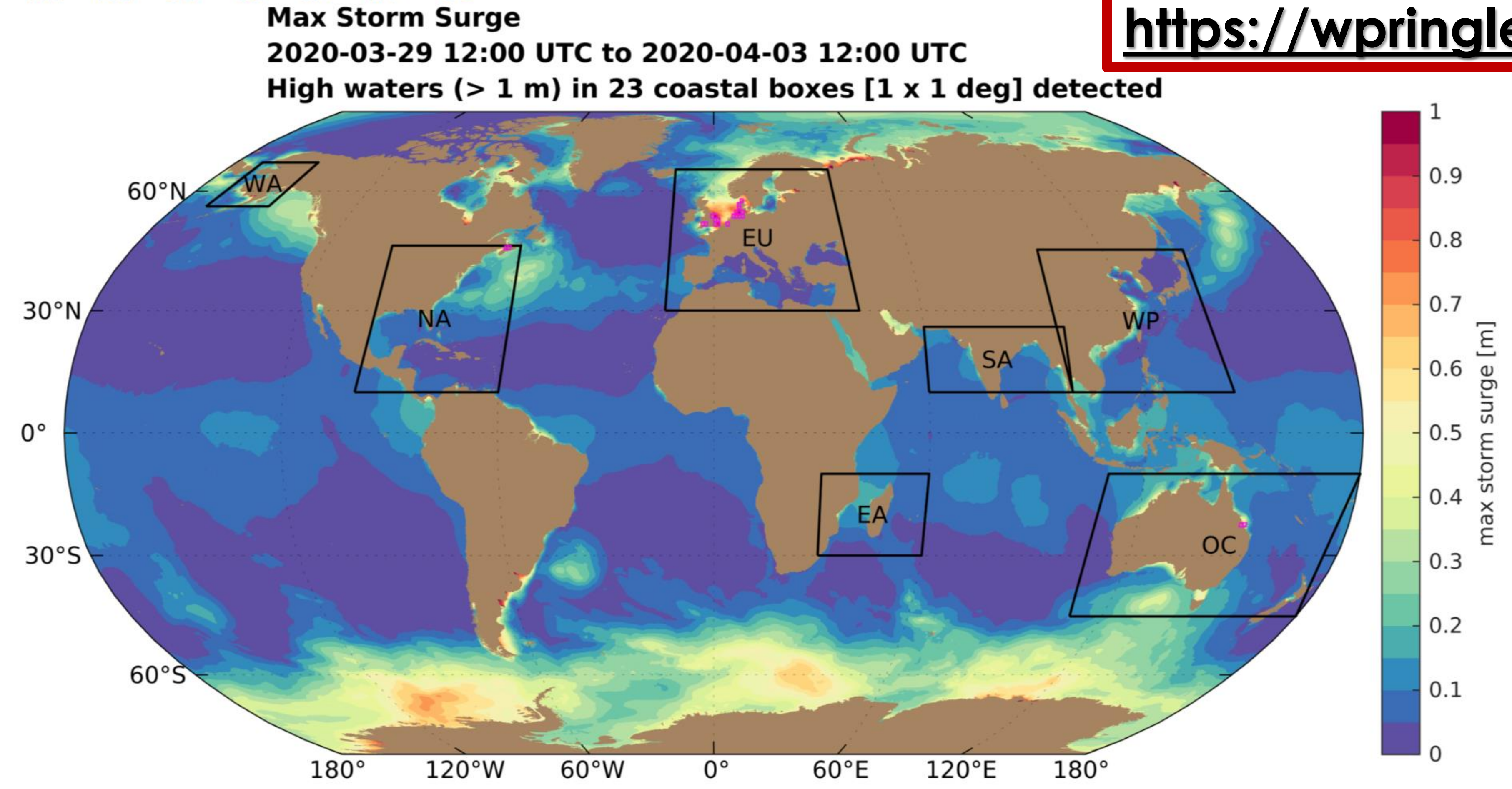
   b. From mass-conservation point of view we should use **constant TAU0**

GLObal Coastal Ocean Flood Forecasting System

An ADCIRC-based global storm tide modeling system providing real-time predictions for coastal flooding

View on GitHub

https://wpringle.github.io/GLOCOFFS/



Continuous 5-day forecasts every 6 hrs

Since April, 2019
1330+ commits